

## THE TOP QUARK

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**A. Introduction:** The top quark is the  $Q = 2/3$ ,  $T_3 = +1/2$  member of the weak-isospin doublet containing the bottom quark (see the review on the “Standard Model of Electroweak Interactions” for more information). This note summarizes the properties of the top quark (mass, production cross section, decay branching ratios, *etc.*), and provides a discussion of the experimental and theoretical issues involved in their determination

**B. Top quark production at the Tevatron:** All direct measurements of production and decay of the top quark have been made by the CDF and DØ experiments in  $p\bar{p}$  collisions at the Fermilab Tevatron collider. The first studies were performed during Run I, at  $\sqrt{s} = 1.8$  TeV, which was completed in 1996. The most recent, and most precise, measurements are from Run II, which started in 2001 at  $\sqrt{s} = 1.96$  TeV. This note will discuss primarily results from Run II.

In hadron collisions, top quarks are produced dominantly in pairs through the QCD processes  $q\bar{q} \rightarrow t\bar{t}$  and  $gg \rightarrow t\bar{t}$ . At  $\sqrt{s} = 1.96$  TeV the most recent calculations are at NLO with next-to-leading-log soft gluon resummation [1]. Cacciari *et al.* gives a production cross section of 7.61 pb for  $m_t = 171$  GeV/ $c^2$  with CTEQ6.5 PDFs. Over the range  $150$  GeV/ $c^2 \leq m_t \leq 190$  GeV/ $c^2$  the calculated cross section decreases (increases) by approximately 0.24 pb/GeV for  $m_t$  greater (less) than 171 GeV/ $c^2$ . A similar calculation by Kidonakis and Vogt yields a production cross section of 7.62 pb for  $m_t = 171$  GeV/ $c^2$  using CTEQ6.6M, with nearly the same mass-dependence. The difference in the central value obtained using different PDFs is typically a few tenths of a pb or less. A detailed comparison of the most recent calculations is ongoing between the authors of the calculations. Approximately 85% of the production cross section at the Tevatron is from  $q\bar{q}$  annihilation, with the remainder from gluon-gluon fusion [2]. Somewhat smaller cross sections are expected from electroweak single-top production

mechanisms, namely from  $q\bar{q}' \rightarrow t\bar{b}$  [3] and  $qb \rightarrow q't$  [4], mediated by virtual  $s$ -channel and  $t$ -channel  $W$  bosons, respectively. The cross sections are calculated for  $m_{top} = 175 \text{ GeV}/c^2$  to be  $0.88 \pm 0.11 \text{ pb}$  for the  $s$ -channel, and  $1.98 \pm 0.25 \text{ pb}$  for the  $t$ -channel [5], a little less than half of the  $t\bar{t}$  production rate. The identification of top quarks in the electroweak single-top channel is much more difficult than in the QCD  $t\bar{t}$  channel, due to a less distinctive signature and significantly larger backgrounds.

In top decay, the  $Ws$  and  $Wd$  final states are expected to be suppressed relative to  $Wb$  by the square of the CKM matrix elements  $V_{ts}$  and  $V_{td}$ . Assuming unitarity of the three-generation CKM matrix, these matrix element values are estimated to be less than 0.043 and 0.014, respectively, implying a value of  $V_{tb} > 0.999$  (see the review “The CKM Quark-Mixing Matrix” for more information). With a mass above the  $Wb$  threshold, and  $V_{tb}$  close to unity, the decay width of the top quark is expected to be dominated by the two-body channel  $t \rightarrow Wb$ . Neglecting terms of order  $m_b^2/m_t^2$ ,  $\alpha_s^2$ , and  $(\alpha_s/\pi)M_W^2/m_t^2$ , the width predicted in the Standard Model (SM) at next-to-leading-order is [6]:

$$\Gamma_t = \frac{GFm_t^3}{8\pi\sqrt{2}} \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{m_t^2}\right) \left[1 - \frac{2\alpha_s}{3\pi} \left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right], \quad (1)$$

where  $m_t$  refers to the top quark pole mass. The width for a value of  $m_t = 171 \text{ GeV}/c^2$ , close to the world average, is  $1.29 \text{ GeV}/c^2$  (we use  $\alpha_s(M_Z) = 0.118$ ) and increases with mass. With its correspondingly short lifetime of  $\approx 0.5 \times 10^{-24} \text{ s}$ , the top quark is expected to decay before top-flavored hadrons or  $t\bar{t}$ -quarkonium-bound states can form [7]. The order  $\alpha_s^2$  QCD corrections to  $\Gamma_t$  are also available [8], thereby improving the overall theoretical accuracy to better than 1%.

The final states for the leading pair-production process can be divided into three classes:

- A.  $t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow q\bar{q}' b q'' \bar{q}''' \bar{b}$ , (46.2%)
- B.  $t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow q\bar{q}' b \ell \bar{\nu}_\ell \bar{b} + \bar{\ell} \nu_\ell b q \bar{q}' \bar{b}$ , (43.5%)
- C.  $t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow \bar{\ell} \nu_\ell b \ell' \bar{\nu}_{\ell'} \bar{b}$ . (10.3%)

The quarks in the final state evolve into jets of hadrons. A, B, and C are referred to as the all-jets, lepton+jets ( $\ell$ +jets),

and dilepton ( $\ell\ell$ ) channels, respectively. Their relative contributions, including hadronic corrections, are given in parentheses. While  $\ell$  in the above processes refers to  $e$ ,  $\mu$ , or  $\tau$ , most of the results to date rely on the  $e$  and  $\mu$  channels. Therefore, in what follows, we will use  $\ell$  to refer to  $e$  or  $\mu$ , unless otherwise noted.

The initial and final-state quarks can radiate gluons that can be detected as additional jets. The number of jets reconstructed in the detectors depends on the decay kinematics, as well as on the algorithm for reconstructing jets used by the analysis. The transverse momenta of neutrinos are reconstructed from the imbalance in transverse momentum measured in each event (missing  $p_T$ , which is here also missing  $E_T$ ).

The observation of  $t\bar{t}$  pairs has been reported in all of the above decay classes. As discussed below, the production and decay properties of the top quark extracted from the three decay classes are consistent within their experimental uncertainty. In particular, the  $t \rightarrow Wb$  decay mode is supported through the reconstruction of the  $W \rightarrow jj$  invariant mass in events with two identified  $b$ -jets in the  $\ell\nu_\ell b\bar{b}jj$  final state [9] and in the all-jets final state [10]. Also the CDF and DØ measurements of the top quark mass in lepton+jets events, where the jet energy scale is calibrated *in situ* using the invariant mass of the hadronically decaying  $W$  boson [11,12], support this decay mode.

The extraction of top-quark properties from Tevatron data relies on a good understanding of the production and decay mechanisms of the top quark, as well as of the background processes. For the background, the jets are expected to have a steeply falling  $E_T$  spectrum, to have an angular distribution peaked at small angles with respect to the beam, and to contain  $b$ - and  $c$ -quarks at the few-percent level. On the contrary, for the top signal, the fraction of events containing  $b$  jets is expected to be  $\approx 100\%$ , and the jets to be rather energetic, since they come from the decay of a massive object. It is therefore possible to improve the S/B ratio by requiring the presence of a  $b$  quark, or by selecting very energetic and central kinematic configurations, or both.

Background estimates can be checked using control samples with fewer jets, where there is little top contamination (0 or 1 jet for dilepton channels, 1 or 2 jets for lepton+jets channels, and  $\leq 4$  jets for multijets).

The cross sections for single-top production are proportional to  $|V_{tb}|^2$ , and no assumption is needed on the number of families or on the unitarity of the CKM matrix in extracting  $|V_{tb}|$ . Separate measurements of the  $s$ - and  $t$ -channel processes provide sensitivity to physics beyond the SM [13]. The single-top process has recently been observed by both DØ [14] and CDF [15]. These results are discussed in a separate section below.

Next-to-leading-order Monte-Carlo programs are now available for the  $t\bar{t}$  production processes [16]. Theoretical estimates of the background processes ( $W$  or  $Z$  bosons+jets and dibosons+jets) using LO calculations have large uncertainties. While this limitation affects estimates of the overall production rates, it is believed that the LO determination of event kinematics, and of the fraction of  $W$ +multi-jet events that contain  $b$ - or  $c$ -quarks, are relatively accurate [17]. Comparison to CDF and DØ data, however, indicates the  $b$ - and  $c$ -quark fractions to be underestimated by the LO generators.

***C. Measured top properties:*** Current measurements of top properties by CDF and DØ are based on Run-II data with integrated luminosities up to  $5.3 \text{ fb}^{-1}$ .

***C.1  $t\bar{t}$  Production Cross Section:*** Both experiments determine the  $t\bar{t}$ -production cross section,  $\sigma_{t\bar{t}}$ , from the observed or estimated number of top candidates, estimated background,  $t\bar{t}$  acceptance, and integrated luminosity. The cross section has been measured in the dilepton, lepton+jets, and all-jets decay modes. To separate signal from background, the experiments use identification of jets likely to contain  $b$ -quarks (“ $b$ -tagging”) and/or discriminating kinematic observables. Techniques used for  $b$ -tagging include identification of a secondary vertex (“vtx  $b$ -tag”), a probability that a jet contains a secondary vertex based on the measured impact parameter of tracks (“jet probability”),

or identification of a muon (electron) from a semileptonic  $b$  decay (“soft  $\mu$  ( $e$ )  $b$ -tag”). CDF and DØ also use artificial neural network-based  $b$ -tagging algorithms that combine the properties of displaced tracks and secondary vertex information.

Due to the lepton identification (ID) requirements in the  $\ell$ +jets and  $\ell\ell$  modes, in particular the  $p_T$  requirement, the sensitivity is primarily to  $e$  and  $\mu$  decays of the  $W$ , with only a small contribution from  $W \rightarrow \tau\nu$  due to secondary  $\tau \rightarrow (e, \mu)\nu X$  decays. In the  $\ell\ell$  mode, when only one lepton is required to satisfy lepton ID criteria ( $\ell$ +track), there is greater sensitivity to  $W \rightarrow \tau\nu$ . CDF uses a missing- $E_T$ +jets selection in the  $\ell$ +jets mode that does not require specific lepton-ID, and therefore has significant acceptance to  $W \rightarrow \tau\nu$  decays, including hadronic  $\tau$  decays, in addition to  $W \rightarrow e\nu, \mu\nu$  decays. In a direct search for the  $\tau$  decay mode of  $t\bar{t}$  pairs in the lepton+hadronic  $\tau$  channel, the ratio  $r_\tau \equiv B(t \rightarrow b\tau\nu)/B_{SM}(t \rightarrow b\tau\nu)$  is found to be  $r_\tau < 5.2$  at 95% C.L. [18]. DØ finds the production cross section (and visible cross section  $\sigma \cdot Br$ ) to be consistent with SM expectations in the lepton+hadronic  $\tau$  channel [19], as well as in the  $\tau$ +jets channel [20] and in the  $\ell\tau$  channel [39]. In the most recent results from CDF, using more than  $4 \text{ fb}^{-1}$ , the measurement is done as a ratio to the  $Z$ -boson production cross section measured using the same dataset and triggers. This removes the uncertainty due to the integrated luminosity measurement and much of the uncertainties due to trigger and lepton ID efficiencies. Table 1 shows the measured cross sections from DØ and CDF. These should be compared to the theoretical calculations that yield  $7.9 - 6.7 \text{ pb}$  for top masses from 170 to 175  $\text{GeV}/c^2$  respectively [1]( see Listings).

Next-to-leading-order calculations predict a forward-backward asymmetry of  $(5 \pm 1.5)\%$  in  $t\bar{t}$  production [21]. The CDF measurement in  $3.2 \text{ fb}^{-1}$  yields  $19.3 \pm 6.9\%$  [22], while the DØ measurement of this asymmetry yields  $12 \pm 8\%$  at the detector level [23] using  $0.9 \text{ fb}^{-1}$ . Though intriguingly larger, both results are presently consistent with the NLO prediction, in view of the large experimental systematics. The asymmetry arises due to interference between production diagrams with

**Table 1:** Cross section for  $t\bar{t}$  production in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV from CDF and DØ. The cross sections are evaluated using an acceptance for  $m_t = 175$  GeV/ $c^2$  unless marked with ‘‡’ or ‘★’, in which case they are evaluated using an acceptance at  $m_t = 172.5$  GeV/ $c^2$  and  $m_t = 170.9$  GeV/ $c^2$ , respectively. Only preliminary results (not yet submitted for publication as of April 2010) are shown; for published results see the Listings. Uncertainties given are the quadrature sum of statistical and systematic uncertainties of each measurement.

$\sigma_{t\bar{t}}(pb)$	Source	$\int \mathcal{L}dt$ (fb $^{-1}$ )	Ref.	Method
$7.3 \pm 1.9$	DØ	2.1	[19]	$\ell\tau$ + b-jets
$6.2 \pm 1.2$	DØ	1.0	[36]	$\ell\ell$ + $\ell$ +track
$5.2 \pm 1.8\star$	DØ	1.0	[37]	$\ell$ +track
$5.1 \pm 4.4$	DØ	0.4	[20]	$\tau$ +jet
$8.4 \pm 1.2$	DØ	0.4	[35]	$\ell\ell$
$7.0 \pm 0.8\ddagger$	CDF	4.3	[40]	$\ell$ + jets/vtx $b$ -tag
$7.1 \pm 0.7\ddagger$	CDF	4.3	[40]	As above w/ ratio to $\sigma(Z)$
$7.8 \pm 2.9$	CDF	1.7	[42]	$\ell$ + jets/soft $e$ $b$ -tag
$7.5 \pm 0.7\ddagger$	CDF	4.6	[43]	$\ell$ + jets/kinematics
$7.6 \pm 0.5\ddagger$	CDF	4.6	[43]	Above w/ ratio to $\sigma(Z)$
$6.9 \pm 1.0\ddagger$	CDF	4.3	[44]	$\ell$ + jets/NN $b$ -tag
$8.0 \pm 0.9\ddagger$	CDF	2.2	[45]	Missing $E_T$ + jets/ $b$ -tag
$6.6 \pm 0.9\ddagger$	CDF	4.5	[46]	$\ell\ell$
$7.3 \pm 0.9\ddagger$	CDF	4.5	[46]	$\ell\ell$ /vtx $b$ -tag
$7.2 \pm 1.3$	CDF	2.9	[47]	All-jets/kin+vtx $b$ -tags
$7.5 \pm 0.5\ddagger$	CDF	4.6	[41]	Combined

initial-state gluon radiation and diagrams with final-state gluon radiation. The discrepancy between the measurements and theoretical predictions has generated an interest in comparisons between  $t\bar{t}$ +jet production cross section calculations and measurements. A recent measurement from CDF [24] in 4.1 fb $^{-1}$  of integrated luminosity yields a cross section of  $1.6 \pm 0.5$  pb, in good agreement with the theoretical value of  $1.79^{+0.16}_{-0.31}$  pb [25].

The theory calculations at next-to-leading-order, including soft-gluon resummation [1], are in good agreement with all the measurements. The increased precision of combined measurements from larger Run-II samples can serve to constrain, or probe, exotic production mechanisms or decay channels that are predicted by some models [26–29]. Such non-SM effects would yield discrepancies between theory and data. New sources of top could also modify kinematic distributions, such as the invariant mass of the  $t\bar{t}$  pair or the transverse momentum ( $p_T$ ) of the top quark. Run-I studies of the  $t\bar{t}$  invariant mass by CDF and DØ [30,31], and of  $p_T$  distributions by CDF [32], show no deviation from expected behavior. DØ [33] also found these kinematic distributions to be consistent with expectations of the SM in Run I. In Run II, distributions of primary kinematic variables such as the lepton  $p_T$ , missing  $E_T$ , and angular variables have been investigated [34–50] and found to be consistent with the SM. Recently, CDF has measured the differential production cross section  $d\sigma/dM_{t\bar{t}}$  in  $2.7 \text{ fb}^{-1}$  [51]. Comparing the shape to the SM expectation, they find a  $p$ -value of 0.28 (for a definition of the  $p$ -value, see the section on hypothesis testing in the review on “STATISTICS” in this *Review*). The  $t\bar{t}$  invariant mass distributions have been studied by both CDF [52] and DØ [53] for direct evidence of narrow resonances, with limits placed on putative  $Z'$  mass of 805 and 820  $\text{GeV}/c^2$ , respectively. CDF has also used the  $M_{t\bar{t}}$  distribution to place limits on the coupling strength of a massive gluon as a function of its mass [54].

***C.2 Electroweak Single-Top Quark Production:*** DØ [14] and CDF [15] have recently announced the discovery of electroweak production of single top quarks. The announcement is the culmination of a multi-year effort that required the use of many advanced analysis techniques to separate the signal from an overwhelming background. In s-channel single-top production, the top quark is accompanied by a bottom quark and the final state is therefore a  $W$  boson and two bottom jets. In t-channel production, the top is accompanied by both a bottom quark and a light quark jet, but the accompanying bottom quark is typically at large pseudorapidity and low transverse

energy and hence escapes detection. The t-channel final state results also dominantly in  $W+2$  jets, with just one of the jets coming from a bottom quark. Event selection therefore requires a high  $p_T$  electron or muon, two to four jets, one of which must be identified as originating from a bottom quark, and missing  $E_T$ . In addition, CDF uses events selected with large missing  $E_T$  and two or three energetic jets. The expected signal-to-background ratio in these samples is about 5%, and the challenge is to separate the signal not just from QCD-produced  $W$ +jets events, but also from  $t\bar{t}$  events which end up in the signal region.

To overcome this challenge, both experiments have used a variety of multivariate techniques, including neural networks, boosted decision trees, multivariate likelihood functions and matrix elements. With the exception of the CDF missing  $E_T$  plus jets analysis, all the analyses use nearly the same datasets. Nevertheless, they are not completely correlated and the final results come from a combination of all analyses. Both experiments use a neural-network technique to combine the individual results into a final result. DØ reports a combined s- plus t-channel cross section of  $3.94 \pm 0.88$  pb (for  $m_t = 170$  GeV/ $c^2$ ), with a corresponding  $p$ -value of  $2.5 \times 10^{-7}$  ( $5.0\sigma$ ), based on  $2.3$  fb $^{-1}$  of integrated luminosity [14]. CDF reports a combined cross section of  $2.3_{-0.5}^{+0.6}$  pb for  $m_t = 175$  GeV/ $c^2$  with a corresponding  $p$ -value of  $3.1 \times 10^{-7}$  ( $5.0\sigma$ ), based on  $3.2$  fb $^{-1}$  of integrated luminosity [15]. A Bayesian analysis yields a combined single-top production cross section of  $2.76_{-0.47}^{+0.58}$  pb [55].

The CKM matrix element  $V_{tb}$  is extracted from the measured cross sections using the ratio to the theoretical values, which assume  $V_{tb} = 1.0$ . The results are summarized in Table 2.

Both experiments have done separate measurements of the s- and t-channel cross sections by reoptimizing the analysis for one or both of the channels separately. In a simultaneous measurement of s- and t-channel cross sections, CDF measures  $2.0_{-0.6}^{+0.7}$  pb and  $0.7 \pm 0.5$  pb, respectively, in  $3.2$  fb $^{-1}$  of data [56], while DØ measures  $1.05 \pm 0.81$  pb and  $3.14_{-0.80}^{+0.94}$  pb, respectively in  $2.3$  fb $^{-1}$  of integrated luminosity [57]. In a separate analysis,



**Table 2:** Measurements of  $|V_{tb}|$  from CDF and DØ single-top results.

$ V_{tb} $ or $ V_{tb}f_1^L $	Source	$\int \mathcal{L}dt$ (fb $^{-1}$ )	Ref.
$ V_{tb}f_1^L  = 1.07 \pm 0.12$	DØ Run II	2.3	[14]
$ V_{tb}  > 0.78$	DØ Run II	2.3	[14]
$ V_{tb}  = 0.91 \pm 0.13$	CDF Run II	3.2	[15]
$ V_{tb}  = 0.88 \pm 0.07$	CDF + DØ Run II	3.2	[55]
$ V_{tb}  > 0.77$	CDF + DØ Run II	3.2	[55]

optimized for the s-channel alone, CDF measures  $1.49_{-0.75}^{+0.92}$  pb in 3.2 fb $^{-1}$  of data [58].

In the SM single-top-quark production yields a nearly 100% polarization of the top-quark spin along the direction, in the top rest frame, of the down-type quark or charged lepton from the W boson decay. This corresponds to the fact that single top quarks produced at the V-A  $Wtb$  vertex are left-handed. Recently CDF has searched for a small right-handed (V+A) component in 3.2 fb $^{-1}$  of integrated luminosity [59]. To discriminate between the SM V-A and a V+A component, the sample is split into a  $\cos\theta < 0$  piece and a  $\cos\theta > 0$  piece, where  $\theta$  is the angle between the lepton and the down-type quark in the top-quark rest frame. The single-top production cross section in the two samples is measured separately, using the multivariate likelihood technique. The result is consistent with no V+A component and a polarization of  $-1_{-0}^{+0.5}$ .

**C.3 Top Quark Mass Measurements:** The top mass has been measured in the lepton+jets, dilepton, and the all-jets channel by both CDF and DØ. At present, the most precise measurements come from the lepton+jets channel containing four or more jets, and large missing  $E_T$ . The samples for the mass measurement are selected using topological or  $b$ -tagging methods. In this channel, four basic techniques are employed to extract the top mass. In the first, the so-called “template method” (TM) [60], an over-constrained (2C) kinematic fit is performed to the hypothesis  $t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow \ell \bar{\nu}_\ell b q \bar{q}' \bar{b}$  for each event, assuming that the four jets of highest

$E_T$  originate from the four quarks in  $t\bar{t}$  decay. There are 24 possible solutions, reflecting the allowed assignment of the final-state quarks to jets, and the two possible solutions for the longitudinal momentum,  $p_z$ , of the neutrino when the  $W$ -mass constraint is imposed on the leptonic  $W$  decay. The number of solutions is reduced to 12 when a jet is  $b$ -tagged and assigned as one of the  $b$  quarks, and to 4 when the event has two such  $b$ -tags. A  $\chi^2$  variable describes the agreement of the measurements with each possible solution under the  $t\bar{t}$  hypothesis given jet-energy resolutions. The solution with the lowest  $\chi^2$  is defined as the best choice, resulting in one value for the reconstructed top quark mass per event. The distribution of reconstructed top-quark mass from the data events is then compared to templates modeled from a combination of signal and background distributions for a series of assumed top masses. The best fit value for the top quark mass and its uncertainty are obtained from a maximum-likelihood fit. In the second method, the “Matrix Element/Dynamic Likelihood Method” (ME/DLM), similar to that originally suggested by Kondo *et al.* [61] and Dalitz and Goldstein [62], a probability for each event is calculated as a function of the top mass, using an LO matrix element for the production and decay of  $t\bar{t}$  pairs. All possible assignments of reconstructed jets to final-state quarks are used, each weighted by a probability determined from the matrix element. The correspondence between measured four-vectors and parton-level four-vectors is taken into account using probabilistic transfer functions. In a third method, the “Ideogram Method” [63,64], which combines some of the features of the above two techniques, each event is compared to the signal and background mass spectrum, weighted by the  $\chi^2$  probability of the kinematic fit for all 24 jet-quark combinations and an event probability. The latter is determined from the signal fraction in the sample and the event-by-event purity, as determined from a topological discriminant in Monte Carlo events. An additional variation on these techniques is the “Multivariate Likelihood” (ML) technique, where an integral over the matrix element is performed for each permutation, and then summed with weights determined by the  $b$ -tagging

information on each jet. Backgrounds are handled in the ML technique by “deweighting” events according to a background probability calculated using variables based on the topology of the event.

With at least four jets in the final state, the dominant systematic uncertainty on the top quark mass is from the uncertainty on the jet-energy scale. CDF (TM, ME, ML) and DØ (ME) have reduced the jet-energy scale uncertainty by performing a simultaneous, *in situ*, fit to the  $W \rightarrow jj$  hypothesis.

There are several techniques that rely solely on tracking, and thus avoid the jet-energy scale uncertainty. One method [65] exploits the fact that, in the rest frame of the top quark, the boost given to the bottom quark has a Lorentz factor  $\gamma_b \approx 0.4 m_t/m_b$ . The measurement of the transverse decay length  $L_{xy}$  of the  $b$ -hadrons from the top quark decay is therefore sensitive to the mass of the top quark. Another uses the correlation between the  $p_T$  spectrum of the leptons from the  $W$ -boson decay and  $m_t$  [67,66]. Finally, a recent measurement [68] uses the invariant mass of the lepton from the  $W$ -boson decay and the muon from a semileptonic decay of the associated B hadron to measure  $m_t$ .

Additional determinations of the top mass come from the dilepton channel with two or more jets and large missing  $E_T$ , and from the all-jets channel. The dilepton channel, with two unmeasured neutrinos, is under-constrained by one measurement. It is not possible to extract a value for the top-quark mass from direct reconstruction without adding additional information. Assuming a value for  $m_t$ , the  $t\bar{t}$  system can be reconstructed up to an eight-fold ambiguity from the choice of associating leptons and quarks to jets, and due to the two solutions for the  $p_z$  of each neutrino. Recently, an analytic solution to the problem has been proposed [69]. At the Tevatron, two basic techniques are employed: one based on templates, and one using matrix elements. The first class of techniques incorporates additional information to render the kinematic system solvable. In this class, there are two techniques that assign a weight as a function of top mass for each event based on solving for either

**Table 3:** Measurements of top quark mass from CDF and DØ.  $\int \mathcal{L} dt$  is given in  $\text{fb}^{-1}$ . Only preliminary results (not yet submitted for publication as of April 2010) are shown; for published results see the Listings. Statistical uncertainties are listed first, followed by systematic uncertainties.

$m_t$ (GeV/ $c^2$ )	Source	$\int \mathcal{L} dt$	Ref.	Method
$173.7 \pm 0.8 \pm 1.6$	DØ Run II	3.6	[73]	$\ell$ +jets/ $b$ -tag, ME( $W \rightarrow jj$ )
$174.7 \pm 2.9 \pm 2.4$	DØ Run II	3.6	[74]	$\ell\ell$ , $\eta(\nu)$ +ME+MWT
$174.2 \pm 0.9 \pm 1.5$	DØ Run I+II	0.1-3.6	[75]	DØ combined selected measurements
$172.8 \pm 0.9 \pm 0.8$	CDF Run II	4.8	[76]	$\ell$ +jets/ $b$ -tag, ML( $W \rightarrow jj$ )
$172.2 \pm 1.2 \pm 1.0$	CDF Run II	4.8	[77]	$\ell$ +jets/ $b$ -tag, TM( $W \rightarrow jj$ )
$172.1 \pm 1.1 \pm 1.0$	CDF Run II	4.8	[77]	$\ell$ +jets TM( $W \rightarrow jj$ ) & $\ell\ell$ $\eta(\nu)$ + $m_{T2}$
$172.4 \pm 1.4 \pm 1.3$	CDF Run II	3.2	[78]	$\ell$ +jets, ME ( $W \rightarrow jj$ )
$176.9 \pm 8.0 \pm 2.7$	CDF Run II	2.7	[66]	$\ell$ +jets, $P_T(\ell)$
$170.6 \pm 2.2 \pm 3.1$	CDF Run II	4.8	[77]	$\ell\ell$ , $\eta(\nu)$
$154.6 \pm 13.3 \pm 2.3$	CDF Run II	2.8	[67]	$\ell\ell$ , $P_T(\ell)$
$172.8 \pm 7.2 \pm 2.3$	CDF Run II	2.8	[79]	$\ell\ell$ , $\ell$ +jets, $P_T(\ell)$
$174.8 \pm 2.4^{+1.2}_{-1.0}$	CDF Run II	2.9	[80]	all jets, TM( $W \rightarrow jj$ )
$165.2 \pm 4.4 \pm 1.9$	CDF Run II	1.9	[81]	all jets, Ideogram ( $W \rightarrow jj$ )
$172.6 \pm 0.9 \pm 1.2$	CDF Run I+II	0.110-3.2	[82]	CDF Combined selected measurements
$172.0 \pm 0.9 \pm 1.3^*$	CDF,DØ (I+II)	0.110-2.0		publ. results, PDG best
$173.1 \pm 0.6 \pm 1.1^{**}$	CDF,DØ (I+II)	0.110-3.6	[83]	publ. or prelim. results

\* PDG uses this TEVEWWG result as its best value. It is a combination of published Run I + II measurements, yielding a  $\chi^2$  of 5.8 for 10 deg. of freedom.

\*\*The TEVEWWG world average is a combination of published Run I and preliminary or pub. Run-II meas., yielding a  $\chi^2$  of 6.3 for 10 deg. of freedom.

the azimuth,  $\phi$ , of each neutrino given an assumed pseudorapidity,  $\eta$ , ( $\eta(\nu)$ ) [70,71], or for  $\eta$  of each neutrino given an assumed  $\phi$ , ( $\phi(\nu)$ ) [72]. An alternative approach, (MWT) [70], solves for  $\eta$  of each neutrino requiring the sum of the neutrino  $\vec{p}_T$ 's to equal the measured missing  $E_T$  vector. In another technique, ( $p_z(t\bar{t})$ ) [72], the kinematic system is rendered solvable by the addition of the requirement that the  $p_z$  of the  $t\bar{t}$  system, equal to the sum of the  $p_z$  of the  $t$  and  $\bar{t}$ , be zero within a Gaussian uncertainty of 180 GeV/ $c$ . In a variation of the  $p_z(t\bar{t})$  technique, the theoretical relation between the top mass and its production

cross section is used as an additional constraint. In most of the techniques in this class, a single mass per event is extracted and a top-mass value found using a Monte Carlo template fit to the single-event masses, in a manner similar to that employed in the lepton+jets TM technique. The DØ ( $\eta(\nu)$ ) analysis uses the shape of the weight distribution as a function of  $m_{top}$  in the template fit. The second class, ME/DLM, uses weights based on the LO matrix element for an assumed mass, given the measured four-vectors (and integrating over the unknowns) to form a joint likelihood as a function of the top mass for the ensemble of fitted events.

The  $P_T$  spectrum of the leptons in the dilepton channel has also been used to extract a top mass measurement [67]. The resulting statistical uncertainty of the measurement is large, but as with the  $L_{xy}$  technique, it is almost free of the systematic uncertainty due to the jet-energy scale.

In the most recent set of CDF results (see Table 3), a measurement has been done using the lepton+jets and dilepton channels simultaneously. In the lepton+jets channel, the TM is used together with an *in situ*  $W \rightarrow jj$  fit. In the dilepton channel,  $\eta(\nu)$  is used plus a fit to the scalar sum of transverse energies ( $H_T$ ), which is sensitive to the top mass.

In the all-jets channel, there is no unknown neutrino momentum to deal with, but the S/B is the poorest. Both CDF and DØ use events with 6 or more jets, of which at least one is  $b$ -tagged. In addition, both experiments have employed a neural network selection, based on an array of kinematic variables to improve the S/B. At DØ, a top-quark mass is reconstructed from the jet-quark combination that best fits the hadronic  $W$ -mass constraint and the equal-mass constraint for the two top quarks. At CDF, the top-quark mass for each event was reconstructed applying the same fitting technique used in the  $\ell$ +jets mode. In the most recent analysis, the *in situ* jet-energy scale calibration from the  $W \rightarrow jj$  fit is also used. At both CDF and DØ, the resulting mass distribution is compared to Monte Carlo templates for various top-quark masses and the background distribution, and a maximum likelihood

technique is used to extract the final measured value of  $m_t$  and its uncertainty.

$D\bar{O}$  also measures the top-quark mass via comparison of the  $t\bar{t}$  production cross section with the SM expectation [38]. This method has the advantage that it is very simple and sensitive to the top quark pole mass, which is a very well defined concept. The fully-inclusive cross-section calculation, used for comparison, contains current best theoretical knowledge with reduced scheme- or scale-dependence.

Recent results are shown in Table 3. See the Top Quark Listings for a complete set of published results. The systematic uncertainty (second uncertainty shown) is comparable to the statistical uncertainty, and is primarily due to uncertainties in the jet-energy scale and in the Monte Carlo modeling. In the Run-II analyses, CDF and  $D\bar{O}$  have controlled the jet-energy scale uncertainty via *in situ*  $W \rightarrow jj$  calibration using the same  $t\bar{t}$  events, as mentioned above.

The Tevatron Electroweak Working Group (TEVEWWG), responsible for the combined CDF/ $D\bar{O}$  average top mass in Table 3, took account of correlations between systematic uncertainties in the different measurements in a sophisticated manner [83]. The Particle Data Group (PDG) uses their combination of published Run-I and Run-II top-mass measurements,  $m_t = 172.0 \pm 1.6 \text{ GeV}/c^2$  (statistical and systematic uncertainties combined in quadrature), as the PDG best value. The latest TEVEWWG world average [83], also including published and some preliminary Run-II results, yields  $m_t = 173.1 \pm 1.3 \text{ GeV}/c^2$  (statistical and systematic uncertainties combined in quadrature).

Given the experimental technique used to extract the top mass, these mass values should be taken as representing the top *pole mass* (see the review “Note on Quark Masses” in this *Review* for more information). The top pole mass, like any quark mass, is defined up to an intrinsic ambiguity of order  $\Lambda_{QCD} \sim 200 \text{ MeV}$  [84]. Ultimately, the precision of the mass measurements will be limited by the theoretical understanding of the relation between the observables and the theoretical definition of the mass.

Recently, DØ has tested CPT invariance in the top sector. They measured the mass difference between  $t$  and  $\bar{t}$  quarks in lepton+jets final states of  $t\bar{t}$  events in  $1 \text{ fb}^{-1}$ . The measured mass difference of  $3.8 \pm 3.7 \text{ GeV}$  is consistent with the equality of  $t$  and  $\bar{t}$  masses [85].

Current global fits performed within the SM or its minimal supersymmetric extension, in which the top-mass measurements play a crucial role, provide indications for a relatively light Higgs (see “ $H^0$  Indirect Mass Limits” in the Particle Listings of this *Review* for more information). Such fits, including  $Z$ -pole data [86] and direct measurements of the mass and width of the  $W$ -boson, yield  $m_t = 179_{-9}^{+12} \text{ GeV}/c^2$  [87]. A fit including additional electroweak precision data (see the review “Electroweak Model and Constraints on New Physics” in this *Review*) yields  $m_t = 174.7_{-7.8}^{+10.0} \text{ GeV}/c^2$  (OUR EVALUATION). Both indirect evaluations are in good agreement with the direct top-quark mass measurements.

**C.4 Top Quark Electric Charge:** The top quark is the only quark whose electric charge has not been measured through production at threshold in  $e^+e^-$  collisions. Since the CDF and DØ analyses on top quark production do not associate the  $b$ ,  $\bar{b}$ , and  $W^\pm$  uniquely to the top or antitop, decays such as  $t \rightarrow W^+\bar{b}$ ,  $\bar{t} \rightarrow W^-b$  are not excluded. A charge  $4/3$  quark of this kind would be consistent with current electroweak precision data. The  $Z \rightarrow \ell^+\ell^-$  and  $Z \rightarrow b\bar{b}$  data, in particular the discrepancy between  $A_{LR}$  from SLC at SLAC and  $A_{FB}^{0,b}$  of  $b$ -quarks and  $A_{FB}^{0,\ell}$  of leptons from LEP at CERN, can be fitted with a top quark of mass  $m_t = 270 \text{ GeV}/c^2$ , provided that the right-handed  $b$  quark mixes with the isospin  $+1/2$  component of an exotic doublet of charge  $-1/3$  and  $-4/3$  quarks,  $(Q_1, Q_4)_R$  [29,88].

CDF and DØ study the top quark charge in double-tagged lepton+jets events and (CDF) single-tagged dilepton events. Assuming the top and antitop quarks have equal but opposite electric charge, then reconstructing the charge of the  $b$ -quark through jet charge discrimination techniques, the  $|Q_{top}| = 4/3$  and  $|Q_{top}| = 2/3$  scenarios can be differentiated. For the exotic model of Chang *et al.* [88] with a top-quark charge  $|Q_{top}| =$

4/3, DØ yields a  $p$ -value, corresponding to the probability of consistency with the exotic model, of 7.8% [89]. CDF excludes the model at 87% C.L. [90]. While these two results are not directly comparable, they both indicate that the observed particle is indeed consistent with being a SM  $|Q_{top}| = 2/3$  quark. More recently CDF has measured the top quark charge using the soft  $e$  or  $\mu$  from semileptonic  $b$ -decays in  $t\bar{t}$  events [91]. The soft lepton carries the flavor information of the bottom quark (with a dilution factor) and a kinematic fitter is used to associate the soft-lepton-tagged jet with either the  $W^+$  or  $W^-$  from the top decay. The result excludes a charge 4/3 top quark at the 95% C.L. and strongly favors the Standard Model charge 2/3 top quark.

**C.5 Top Branching Ratio:** CDF and DØ report direct measurements of the  $t \rightarrow Wb$  branching ratio [34,92–93]. Comparing the number of events with 0, 1 and 2 tagged  $b$  jets in the lepton+jets channel, and for CDF also in the dilepton channel, and using the known  $b$ -tagging efficiency, the ratio  $R = B(t \rightarrow Wb) / \sum_{q=d,s,b} B(t \rightarrow Wq)$  can be extracted. DØ performs a simultaneous fit for the number of  $t\bar{t}$  events and the ratio  $R$ . A deviation of  $R$  from unity would imply either non-SM top decay, a non-SM background to  $t\bar{t}$  production, or a fourth generation of quarks. The results are summarized in Table 4.

**Table 4:** Measurements and 95% C.L. lower limits of  $R = B(t \rightarrow Wb) / B(t \rightarrow Wq)$  from CDF and DØ. A complete set of published results can be found in the Listings.

$R$	Source	$\int \mathcal{L} dt$ (pb $^{-1}$ )	Ref.
$R = 0.97^{+0.09}_{-0.08}$	DØ Run II	900	[34]
$R > 0.79$	DØ Run II	900	[34]



**C.6 *W*-Boson Helicity:** Studies of decay angular distributions provide a direct check of the  $V-A$  nature of the  $Wtb$  coupling and information on the relative coupling of longitudinal and transverse  $W$  bosons to the top quark. In the SM, the fraction of decays to longitudinally polarized  $W$  bosons is expected to be [94]  $\mathcal{F}_0^{\text{SM}} \approx x/(1+x)$ ,  $x = m_t^2/2M_W^2$  ( $\mathcal{F}_0^{\text{SM}} \sim 70\%$  for  $m_t = 175 \text{ GeV}/c^2$ ). Fractions of left-handed, right-handed, and longitudinal  $W$  bosons are denoted as  $\mathcal{F}_-$ ,  $\mathcal{F}_+$ , and  $\mathcal{F}_0$  respectively. In the SM,  $\mathcal{F}_-$  is expected to be  $\approx 30\%$  and  $\mathcal{F}_+ \approx 0\%$ . CDF and DØ use various techniques to measure the helicity of the  $W$  boson in top quark decays, in both the lepton+jets events and dilepton channels. The first method uses a kinematic fit, similar to that used in the lepton+jets mass analyses, but with the top quark mass constrained to  $175 \text{ GeV}/c^2$ , to improve the reconstruction of final-state observables, and render the under-constrained dilepton channel solvable. The distribution of the helicity angle ( $\cos \theta^*$ ) between the lepton and the  $b$  quark in the  $W$  rest frame provides the most direct measure of the  $W$  helicity. The second method ( $p_T^\ell$ ) uses the different lepton  $p_T$  spectra from longitudinally or transversely polarized  $W$ -decays to determine the relative contributions. A third method uses the invariant mass of the lepton and the  $b$ -quark in top decays ( $M_{\ell b}^2$ ) as an observable, which is directly related to  $\cos \theta^*$ . Finally, the Matrix Element method (ME) has also been used, in which a likelihood is formed from a product of event probabilities calculated from the ME for a given set of measured kinematic variables and assumed  $W$ -helicity fractions. The results of recent CDF and DØ analyses are summarized in Table 5. The datasets are now large enough to allow for a simultaneous fit of  $\mathcal{F}_0$  and  $\mathcal{F}_+$ , which we denote by ‘2-param’ in the table. Results with either  $\mathcal{F}_0$  or  $\mathcal{F}_+$  fixed at its SM value are denoted ‘1-param’. For the simultaneous fits the correlation coefficient between the two values is about  $-0.8$  for both experiments. A complete set of published results can be found in the Listings. All results are in agreement with the SM expectation.

**Table 5:** Measurement and 95% C.L. upper limits of the  $W$  helicity in top quark decays. Published results are given in the Listings. Results listed are preliminary and not yet submitted for publication, as of April 2010.

$W$ Helicity	Source	$\int \mathcal{L} dt$ (fb $^{-1}$ )	Ref.	Method
$\mathcal{F}_0 = 0.70 \pm 0.08$	CDF Run II	2.7	[95]	ME 1-param
$\mathcal{F}_0 = 0.88 \pm 0.13$	CDF Run II	2.7	[95]	ME 2-param
$\mathcal{F}_0 = 0.49 \pm 0.14$	DØ Run II	2.7	[96]	$\cos \theta^*$ 2-param
$\mathcal{F}_+ = -0.01 \pm 0.05$	CDF Run II	2.7	[95]	ME 1-param
$\mathcal{F}_+ = -0.15 \pm 0.09$	CDF Run II	2.7	[95]	ME 2-param
$\mathcal{F}_+ = 0.110 \pm 0.079$	DØ Run II	2.7	[96]	$\cos \theta^*$ 2-param

**C.7  $t\bar{t}$  Spin Correlations & Top Width:** The  $t$  and  $\bar{t}$  are expected to be unpolarized, but to be correlated in their spins. Since top quarks decay before hadronizing, their spins at production are transmitted to their decay-daughter particles. Spin correlation is studied by analyzing the joint decay angular distribution of one  $t$  daughter and one  $\bar{t}$  daughter. The sensitivity to top spin is greatest when the daughters are down-type fermions (charged leptons or  $d$ -type quarks), in which case, the joint distribution is [97–99]

$$\frac{1}{\sigma} \frac{d^2\sigma}{d(\cos\theta_+)d(\cos\theta_-)} = \frac{1 + \kappa \cdot \cos\theta_+ \cdot \cos\theta_-}{4}, \quad (2)$$

where  $\theta_+$  and  $\theta_-$  are the angles of the daughters in the top rest frames with respect to a particular spin quantization axis. The maximum value for  $\kappa$ , 0.782 at NLO at the Tevatron [100], is found in the off-diagonal basis [97]. An alternative basis is the beam direction, which yields  $\kappa = 0.777$  at the Tevatron.

DØ has measured  $\kappa$  in the dilepton sample using the neutrino weighting technique to reconstruct the  $t$  and  $\bar{t}$  rest frames, in which the angles  $\theta_+$  and  $\theta_-$  are measured. Using an integrated luminosity of 4.2 fb $^{-1}$  they measure  $\kappa = -0.17^{+0.64}_{-0.53}$  [101]. Using 2.8 fb $^{-1}$  of integrated luminosity, CDF measures  $\kappa$  in the dilepton sample using a full-reconstruction

method similar to the  $p_z(t\bar{t})$  technique used in the mass measurement in dileptons, but with the inclusion of  $p_T(t\bar{t})$  and  $M_{(t\bar{t})}$  probability distribution functions. The result is a 68% confidence interval of  $-0.455 < \kappa < 0.865$  corresponding to a central value of  $\kappa = 0.320_{-0.775}^{+0.545}$  [102]. Recently CDF has measured  $\kappa$  in lepton plus jets events using an integrated luminosity of  $4.3 \text{ fb}^{-1}$ . A  $\chi^2$  adapted from the TM mass measurement is used to assign observed objects to the  $W^+b$  and  $W^-\bar{b}$  from  $t$  and  $\bar{t}$ , while constraining the top mass at  $172.5 \text{ GeV}/c^2$ , allowing reconstruction of the respective rest frames. With this technique a value of  $\kappa = 0.60 \pm 0.52$  is measured [103].

Because production through gluon fusion produces predominantly like-helicity  $t\bar{t}$  pairs, whereas production through  $q\bar{q}$  annihilation produces predominantly opposite-helicity pairs [99], the putative spin correlations can be used to extract the fraction of  $t\bar{t}$  pairs produced through each of these mechanisms. In  $2 \text{ fb}^{-1}$  of integrated luminosity, CDF has used the azimuthal correlation of the charged leptons in the dilepton decay channel to measure the fraction of  $t\bar{t}$  production from gluon fusion,  $F_{gg}$ , and find  $F_{gg} = 0.53_{-0.38}^{+0.36}$  [104], to be compared with the expectation of approximately 0.15 in the SM.

Related to the measurement of top-spin correlations, which requires a top lifetime less than the hadronization timescale, is the measurement of the top width. The top width is expected to be of order  $1 \text{ GeV}/c^2$  (Eq. 1). The sensitivity of current experiments does not approach this level in direct measurements. CDF has made the first direct measurement of the top width using the mass fitting template method in lepton+jets events, fixing the top mass at  $175 \text{ GeV}/c^2$  and varying the top width in constructing the Monte Carlo templates. The top width is found to be less than  $7.5 \text{ GeV}/c^2$  at the 95% C.L. [105].

DØ extracts the total width of the top quark from the partial decay width  $\Gamma(t \rightarrow Wb)$  and the branching fraction  $B(t \rightarrow Wb)$ .  $\Gamma(t \rightarrow Wb)$  is obtained from the measured  $t$ -channel cross section for single top quark production in  $2.3 \text{ fb}^{-1}$ , and  $B(t \rightarrow Wb)$  is extracted from a measurement of the ratio  $R = B(t \rightarrow Wb)/B(t \rightarrow Wq)$  in  $t\bar{t}$  events in lepton+jets channels with 0, 1 and 2 b-tags in  $1 \text{ fb}^{-1}$  of integrated luminosity. Assuming

$B(t \rightarrow Wq) = 1$ , where  $q$  includes any kinematically accessible quark, the result is:  $\Gamma_t = 2.1 \pm 0.6$  GeV which translates to a top quark lifetime of  $\tau_t = (3 \pm 1) \times 10^{-25}$  s. The use of the partial width measurement alone yields the limits  $\Gamma_t > 1.2$  GeV and  $\tau_t < 5 \times 10^{-25}$  s, at 95% C.L. [106].

**C.8 Non-SM  $t\bar{t}$  Production:** Motivated by the large mass of the top quark, several models suggest that the top quark plays a role in the dynamics of electroweak symmetry breaking. One example is topcolor [26], where a large top quark mass can be generated through the formation of a dynamic  $t\bar{t}$  condensate,  $X$ , which is formed by a new strong gauge force coupling preferentially to the third generation. Another example is topcolor-assisted technicolor [27], predicting a heavy  $Z'$  boson that couples preferentially to the third generation of quarks with cross sections expected to be visible at the Tevatron. CDF and DØ have searched for  $t\bar{t}$  production via intermediate, narrow-width, heavy-vector bosons  $X$  in the lepton+jets channels. The possible  $t\bar{t}$  production via an intermediate resonance  $X$  is sought for as a peak in the spectrum of the invariant  $t\bar{t}$  mass. CDF and DØ exclude narrow-width heavy-vector bosons  $X$  in the top-assisted technicolor model [107], with mass  $M_X < 480$  GeV/ $c^2$  and  $M_X < 560$  GeV/ $c^2$ , respectively, in Run I [30,31], and  $M_X < 805$  GeV/ $c^2$  and  $M_X < 820$  GeV/ $c^2$  in Run II [52,53]. With 955 pb $^{-1}$  of Run-II data, CDF has produced a less model-dependent limit for a narrow-width  $Z'$ , ruling out at the 95% C.L. a contribution greater than 0.64 pb for a  $Z'$  heavier than 700 GeV/ $c^2$  decaying to  $t\bar{t}$  [108]. Using a measurement of the forward-backward asymmetry in  $t\bar{t}$  production, DØ extracts a 95% C.L. limit on the fraction of  $t\bar{t}$  pairs produced by a  $Z'$  resonance as a function of the  $Z'$  mass [23]. A recent CDF analysis has placed limits on the coupling strength of a massive gluon to  $t\bar{t}$  [54]. In 0.9 fb $^{-1}$  and 3.1 fb $^{-1}$ , DØ has set limits on scalar top-quark pair production, with subsequent decays to top quarks in the lepton+jets and the dilepton channel, respectively [50,109].

The existence of flavor-changing neutral-currents (FCNC) couplings can enhance the rate of single-top quark production, and both experiments have used upper limits on the observed

rate to place limits on these couplings. In 230 pb<sup>-1</sup> of Run-II data, DØ uses their single-top analysis to place limits on anomalous production via the FCNC coupling of a gluon to the top quark and a charm ( $tcg$ ) or up quark ( $tug$ ) [110]. The observed limits are at 95% C.L.:  $\kappa_{gtc}/\Lambda < 0.15$  TeV<sup>-1</sup> and  $\kappa_{gtu}/\Lambda < 0.037$  TeV<sup>-1</sup>. CDF has searched for FCNC in the s-channel  $Wtb$  production vertex. In 2.2 fb<sup>-1</sup> of integrated luminosity, CDF sets limits on the couplings of  $\kappa_{gtc}/\Lambda < 0.105$  TeV<sup>-1</sup> and  $\kappa_{gtu}/\Lambda < 0.025$  TeV<sup>-1</sup> [111].

**C.9 Non-SM Top Decays:** Both CDF and DØ have searched for non-SM top decays [112–116], particularly those expected in supersymmetric models, such as  $t \rightarrow H^+b$ , followed by  $H^+ \rightarrow \tau^+\bar{\nu}$  or  $c\bar{s}$ . The  $t \rightarrow H^+b$  branching ratio has a minimum at  $\tan\beta = \sqrt{m_t/m_b} \simeq 6$ , and is large in the region of either  $\tan\beta \ll 6$  or  $\tan\beta \gg 6$ . In the former range,  $H^+ \rightarrow c\bar{s}$  is dominant, while  $H^+ \rightarrow \tau^+\bar{\nu}$  dominates in the latter range. These studies are based either on direct searches for these final states, or on top “disappearance.” In the standard lepton+jets or dilepton cross-section analyses, any charged-Higgs decays are not detected as efficiently as  $t \rightarrow W^\pm b$ , primarily because the selection criteria are optimized for the standard decays, and because of the absence of energetic isolated leptons in Higgs decays. A significant  $t \rightarrow H^+b$  contribution would give rise to measured  $t\bar{t}$  cross sections that would be lower than the prediction from the SM (assuming that non-SM contributions to  $t\bar{t}$  production are negligible), and the measured cross-section ratio  $\sigma_{t\bar{t}}^{\ell+jets}/\sigma_{t\bar{t}}^{\ell\ell}$  would differ from unity.

In Run II, CDF has searched for charged-Higgs production in dilepton, lepton+jets, and lepton+hadronic tau final states, considering possible  $H^+$  decays to  $c\bar{s}$ ,  $\tau\bar{\nu}$ ,  $t^*b$ , or  $W^+h^0$ , in addition to the SM decay  $t \rightarrow W^+b$  [114,115]. Depending on the top and Higgs-decay branching ratios, which are scanned in a particular 2-Higgs doublet benchmark model, the number of expected events in these decay channels can show an excess or deficit when compared to SM expectations. A model-independent interpretation yields a limit of  $B(t \rightarrow H^\pm b) < 0.91$  at 95% C.L. for  $m_{H^\pm} \approx 100$  GeV, and  $B(t \rightarrow H^\pm b) < 0.4$  in the tauonic model with  $B(H^\pm \rightarrow \tau\nu) = 100\%$ . In a more

recent search, the dijet invariant mass in lepton+jets events has been used to search for a charged Higgs decaying to  $c\bar{s}$  with mass above the  $W$  boson mass. The absence of a signal leads to a 95% C.L. limit of  $B(t \rightarrow H^\pm b) < 0.1$  to 0.3 for masses between 60 and 150 GeV/c<sup>2</sup> [115]. In 1 fb<sup>-1</sup> of integrated luminosity, the DØ collaboration has used the  $t\bar{t}$  dilepton and lepton+jets events, including  $\tau$  lepton channels, to search for evidence of charged-Higgs decays into  $\tau$  leptons via the ratio of events with  $\tau$  leptons to those with  $e$  and  $\mu$  [38], global fits [117] and topological searches [118]. They exclude regions of  $B(t \rightarrow H^\pm b)$  as a function of Higgs mass, ranging from  $B(t \rightarrow H^\pm b) > 0.12$  at low mass to  $B(t \rightarrow H^\pm b) > 0.2$  at high mass. In a companion analysis they look for evidence of leptophobic charged Higgs production in top decays in which the Higgs decays purely hadronically, leading to a suppression of the measured  $t\bar{t}$  rate in all leptonic channels. They exclude  $B(t \rightarrow H^\pm b) > 0.2$  for charged-Higgs masses between 80 and 155 GeV/c<sup>2</sup>.

More details, and the results of these studies for the exclusion in the  $m_{H^\pm}, \tan\beta$  plane, can be found in the review “Search for Higgs bosons” and in the “ $H^+$  Mass Limits” section of the Higgs Particle Listings of the current edition.

In the SM, the top-quark lifetime is expected to be about  $0.5 \times 10^{-24}$  s ( $c\tau_t \approx 1.5 \times 10^{-10}$   $\mu\text{m}$ ), while additional quark generations, non-standard top-quark decays, or other extensions of the SM could yield long-lived top quarks in the data. CDF has studied the top-quark lifetime by measuring the distance between the initial  $p\bar{p}$  scattering and the leptonic  $W^\pm$  decay vertex in lepton+jets events [119]. The measured lifetime is consistent with zero, and an upper limit  $c\tau_t < 52.5$   $\mu\text{m}$  is found at 95% C.L. DØ extracts the lifetime to be  $\tau_t = (3 \pm 1) \times 10^{-25}$  s from the  $t$ -channel cross section for single top quark production and the measurement of the ratio  $R = B(t \rightarrow Wb)/B(t \rightarrow Wq)$  [106].

Using up to 2.7 fb<sup>-1</sup> of data, DØ has measured the  $Wtb$  coupling form factors by combining information from the  $W$  boson helicity in top quark decays in  $t\bar{t}$  events and single-top

quark production, allowing to place limits on the left-handed and right-handed vector and tensor couplings [120,121].

$D\bar{O}$  excludes the production of  $W'$  bosons with masses below 731 GeV for a  $W'$  boson with standard-model-like couplings, below 739 GeV for a  $W'$  boson with right-handed couplings that is allowed to decay to both leptons and quarks, and below 768 GeV for a  $W'$  boson with right-handed couplings that is only allowed to decay to quarks [122]. CDF has recently released  $W'$  limits also using the single-top analysis [123]. In  $1.9 \text{ fb}^{-1}$  of Run-II data, a  $W'$  with Standard-Model couplings is searched for in the  $t\bar{b}$  decay mode. Masses below 800 GeV are excluded, assuming that any right-handed neutrino is lighter than the  $W'$ , and below 825 GeV if the right-handed neutrino is heavier than the  $W'$ .

CDF reported a search for flavor-changing neutral-current (FCNC) decays of the top quark  $t \rightarrow q\gamma$  and  $t \rightarrow qZ$  in the Run-I data [124], and recently with enhanced sensitivity in Run II [125]. The SM predicts such small rates that any observation would be a sign of new physics. CDF assumes that one top decays via FCNC, while the other decays via  $Wb$ . The Run-I analysis included a  $t \rightarrow q\gamma$  search in which two signatures are examined, depending on whether the  $W$  decays leptonically or hadronically. For leptonic  $W$  decay, the signature is  $\gamma\ell$  and missing  $E_T$  and two or more jets, while for hadronic  $W$  decay, it is  $\gamma + \geq 4$  jets. In either case, one of the jets must have a secondary vertex  $b$  tag. One event is observed ( $\mu\gamma$ ) with an expected background of less than half an event, giving an upper limit on the top branching ratio of  $B(t \rightarrow q\gamma) < 3.2\%$  at 95% C.L. In the search for  $t \rightarrow qZ$ , CDF considers  $Z \rightarrow \mu\mu$  or  $ee$  and  $W \rightarrow qq'$ , giving a  $Z + \text{four jets}$  signature. A Run-II dataset of  $1.9 \text{ fb}^{-1}$  is found consistent with background expectations and a 95% C.L. on the  $t \rightarrow qZ$  branching fraction of  $< 3.7\%$  (for  $M_{\text{top}}=175 \text{ GeV}/c^2$ ) is set. By comparison to the number expected from the theoretical production cross section, CDF has used the observed number of double b-tagged lepton+jets candidate events to place limits on a variety of decay modes, ranging from  $B(t \rightarrow Zc) < 13\%$  to  $B(t \rightarrow \text{invisible}) < 9\%$  [126].

Constraints on FCNC couplings of the top quark can also be obtained from searches for anomalous single-top production in  $e^+e^-$  collisions, via the process  $e^+e^- \rightarrow \gamma, Z^* \rightarrow t\bar{q}$  and its charge-conjugate ( $q = u, c$ ), or in  $e^\pm p$  collisions, via the process  $e^\pm u \rightarrow e^\pm t$ . For a leptonic  $W$  decay, the topology is at least a high- $p_T$  lepton, a high- $p_T$  jet and missing  $E_T$ , while for a hadronic  $W$ -decay, the topology is three high- $p_T$  jets. Limits on the cross section for this reaction have been obtained by the LEP collaborations [127] in  $e^+e^-$  collisions, and by H1 [128] and ZEUS [129] in  $e^\pm p$  collisions. When interpreted in terms of branching ratios in top decay [130,131], the LEP limits lead to typical 95% C.L. upper bounds of  $B(t \rightarrow qZ) < 0.137$ . Assuming no coupling to the  $Z$  boson, the 95% C.L. limits on the anomalous FCNC coupling  $\kappa_\gamma < 0.17$  and  $< 0.27$  by ZEUS and H1, respectively, are stronger than the CDF limit of  $\kappa_\gamma < 0.42$ , and improve over LEP sensitivity in that domain. The H1 limit is slightly weaker than the ZEUS limit due to an observed excess of five-candidate events over an expected background of  $3.2 \pm 0.4$ . If this excess is attributed to FCNC top-quark production, this leads to a total cross section of  $\sigma(ep \rightarrow e + t + X, \sqrt{s} = 319 \text{ GeV}) < 0.25 \text{ pb}$  [128,132].

***Appendix. Expected Sensitivity at the LHC:***

The top pair-production cross section at the LHC at  $\sqrt{s} = 14 \text{ TeV}$  is predicted at NLO to be about 800 pb [133]. In the first years, the LHC will operate at  $\sqrt{s} = 7 \text{ TeV}$ , yielding an expected cross section of about 170 pb [134]. At  $\sqrt{s} = 14 \text{ TeV}$  there will be 8 million  $t\bar{t}$  pairs produced per year at a luminosity of  $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ . Such large event samples will permit precision measurements of the top-quark parameters. The statistical uncertainties on  $m_t$  will become negligible, and will allow to monitor the systematic uncertainties at a level at least comparable to the current Tevatron uncertainty on  $m_{top}$  [135–137].

Precision measurements of the top pair-production cross section are expected to be limited by the estimated 3-10% accuracy on the luminosity determination [135,136], but far more accurate measurements would be available from the ratio of the  $t\bar{t}$  production to inclusive  $W$  or  $Z$  production.



Single-top production will also be of keen interest at the LHC, where a  $|V_{tb}|$  measurement at the 5% level per experiment is projected with  $10 \text{ fb}^{-1}$  [135,136].

Tests of the  $V - A$  nature of the  $tWb$  vertex through a measurement of the  $W$  helicity will be extended from the Tevatron to the LHC. Current estimates are that the longitudinal fraction can be measured with a precision of about 5% [136] with  $10 \text{ fb}^{-1}$  of data.

Top-antitop spin correlations should be relatively easy to observe and measure at the LHC, where the preferred dilepton mode will have large event samples, despite the small branching fraction. At the LHC, where  $t\bar{t}$  is dominantly produced through gluon fusion, the correlation is such that the top quarks are mainly either both left- or both right-handed. The CMS collaboration [136] estimates that the relative asymmetry (defined as the difference in the fraction of like-handed and the fraction of oppositely-handed  $t\bar{t}$  pairs) can be measured to about 17% accuracy with  $10 \text{ fb}^{-1}$  of data.

In addition to these SM measurements, the large-event samples will allow sensitive searches for new physics. The search for heavy resonances that decay to  $t\bar{t}$ , already begun at the Tevatron, will acquire enhanced reach both in mass and  $\sigma \cdot B$ . The ATLAS collaboration [135] has studied the reach for a  $5\sigma$  discovery of a narrow resonance decaying to  $t\bar{t}$ . With  $30 \text{ fb}^{-1}$ , it is estimated that a resonance can be discovered at  $4 \text{ TeV}/c^2$  for  $\sigma \cdot B = 10 \text{ fb}$ , and at  $1 \text{ TeV}/c^2$  for  $\sigma \cdot B = 1000 \text{ fb}$ . FCNC decays,  $t \rightarrow Zq, \gamma q, gq$ , can take place in the SM, or in the MSSM, but at rates too small to be observed even at the LHC. As such, searches for these decay modes can provide sensitive tests of other extensions of the SM [135,136]. Updated sensitivity studies at  $\sqrt{s} = 10 \text{ TeV}$  by the ATLAS Collaboration are available at [138]. Recently, the CERN management decided to start proton-proton collisions in late 2009 at  $\sqrt{s} = 7 \text{ TeV}$ . The production rates and the estimated sensitivities change accordingly.

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